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RECTIFICATION IN NONLINEAR SYMMETRICAL ELECTRIC AND MAGNETIC CIRCUITS

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All present-day static rectifiers are based on the use of nonlinear elements with asymmetric volt-ampere characteristics. If the dependence of the current I, flowing through an element, upon the applied voltage U is expressed in the form:

$$I=f(U), \qquad \text{(a)}$$

then what we mean by elements with asymmetric characteristics are those elements expressed by:

$$f=(-U)\neq -f(U) \quad \text{[probably error for } f(-U)\neq -f(U)\text{]} \qquad \text{(b)}$$

If a sinusoidal voltage is impressed upon the input terminals of a nonlinear element with symmetrical characteristics, that is, an element expressible by:

$$f(-U)=-f(U) \qquad \text{(c)}$$

then rectification does not hold. The form of the curve describing the current I flowing through a nonlinear element is merely distorted. If the voltage at the input terminals of a nonlinear element contains two components differing in frequency. then, as will be shown, rectification can hold for certain definite ratios between these two frequencies.

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The characteristic of a symmetrical nonlinear element can be approximated by the polynomial:

$$I = \sum_{k=0}^{n} a_{2k+1} U^{2k+1}, \tag{1}$$

which contains the voltage U in odd powers. The highest power, namely 2n + 1, of the above polynomial we shall call the order of nonlinearity.

First, let us discuss elements with nonlinearity of order three, for which case we then have:

$$I = a_1 U + a_3 U^3. \tag{d}$$

Let us assume:

$$U = A \cos pt + B \cos (qt + \alpha) \tag{e}$$

Then after suitable transformations we find the current I expressed as:

$$\begin{aligned} I = {} & (a_1 A + \tfrac{3}{4} a_3 A^3 + \tfrac{3}{2} a_3 A B^2) \cos pt + \tfrac{1}{4} a_3 A^3 \cos 3pt + \\ & + (a_1 B + \tfrac{3}{4} a_3 B^3 + \tfrac{3}{2} a_3 A^2 B) \cos (qt + \alpha) + \tfrac{1}{4} a_3 B^3 \cos 3(qt + \alpha) + \\ & + \tfrac{3}{4} a_3 A^2 B \cos (2pt + qt + \alpha) + \tfrac{3}{4} a_3 A B^2 \cos (pt + 2qt + 2\alpha) + \\ & + \tfrac{3}{4} a_3 A^2 B \cos (qt - 2pt + \alpha) + \tfrac{3}{4} a_3 A B^2 \cos (2qt - pt + 2\alpha). \end{aligned} \tag{f}$$

From these formulas it is evident that rectification takes place if the ratio p/q equals ½ and 2. In these cases, we obtain, correspondingly, the following values of the constant component of the current:

$$\underset{(\text{for } p/q = 1/2)}{I_0 = \tfrac{3}{4} a_3 A^2 B \cos \alpha}, \qquad \underset{(\text{for } p/q = 2)}{I_1 = \tfrac{3}{4} a_3 A B^2 \cos 2\alpha} \tag{h}$$

The rectified current in both cases attains its maximum value for a null argument in the cosine function, that is, for angle of lead alpha $\alpha = 0$.

If we carry through similar calculations for the case of nonlinearity of the fifth order, then it turns out that rectification is possible for the following six values of the ratio p/q:

$$\frac{p}{q} = \frac{1}{4};\ \frac{2}{3};\ \frac{3}{2};\ \frac{4}{1};\ \frac{1}{2} \text{ and } \frac{2}{1} \tag{j}$$

For a nonlinearity of the seventh order, rectification holds if the ratio of frequencies equals:

$$\frac{p}{q} = \frac{1}{6};\ \frac{2}{5};\ \frac{3}{4};\ \frac{4}{3};\ \frac{5}{2};\ \frac{6}{1};\ \frac{1}{4};\ \frac{2}{3};\ \frac{3}{2};\ \frac{4}{1};\ \frac{1}{2} \text{ and } \frac{2}{1} \tag{k}$$

In the general case of nonlinearity of order $2n+1$ rectification will occur for the following ratios of frequencies:

$$\frac{p}{q}=\frac{1}{2n};\ \frac{2}{2n-1};\ \frac{3}{2n-2};\ \ldots;\ \frac{2n-2}{3};\ \frac{2n-1}{2};\ \frac{2n}{1};$$

$$\frac{1}{2n-2};\ \frac{2}{2n-3};\ \frac{3}{2n-4};\ \ldots;\ \frac{2n-4}{3};\ \frac{2n-3}{2};\ \frac{2n-2}{1};$$

$$\frac{1}{2n-4};\ \frac{2}{2n-5};\ \frac{3}{2n-6};\ \ldots;\ \frac{2n-6}{3};\ \frac{2n-5}{2};\ \frac{2n-4}{1}; \qquad \text{(m)}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\frac{1}{6};\ \frac{2}{5};\ \frac{3}{4};\ \frac{4}{3};\ \frac{5}{2};\ \frac{6}{1};$$

$$\frac{1}{4};\ \frac{2}{3};\ \frac{3}{2},\ \frac{4}{1},$$

$$\frac{1}{2};\ \frac{2}{1}.$$

Here the magnitude of the rectified current depends upon the lead angle alpha α and always attains its maximum value when this angle is zero.

Rectification takes place not only in electrical circuits but also in nonlinear symmetrical magnetic circuits. If a ferromagnetic material is subjected to magnetization by fields of two different frequencies, then, for ratios of these frequencies equal to values deduced above, a constant component of magnetic induction will appear in the magnetic material, in spite of the absence of a constant component of the magnetomotive force.

The magnitude of the constant component of magnetic induction, appearing as a result of magnetic rectification, can be found if, in the formula approximating the curve of magnetization, one substitutes the intensity of the variable magnetic fields, or if one makes the corresponding graphic construction.

The phenomenon of magnetic rectification was observed by us in the following experiment. On the outer two legs of a three-legged transformer core, made out of permalloy, were placed core windings W_1 which were connected in such a manner that a magnetic flux Φ, was generated in the two outer core legs when a current passed through the core windings W_1. These core windings were connected to a 50-cycle AC network. A core winding W_2 around the middle core leg was connected to a vacuum-tube oscillator, which made it possible to vary over a wide range the frequency of the voltage U_2 at the input terminals of core winding W_2. In this scheme, we succeeded in practically avoiding the influence of one circuit upon the other. At a distance about 80 millimeters from the transformer core we placed a magnetic needle M. The axis of symmetry 0 - 0 of the transformer core was set perpendicular to the magnetic meridian. The ratio of frequencies of the voltages U_1 and U_2, consequently, of the fluxes Φ_1, , and Φ_2, were controlled by means of Lissajou's figures as observed on the oscilloscope.

We express here the value of the angle of declination φ of the magnetic needle M from the direction of the magnetic meridian as a function of the frequency f_2 of the voltage U_2 thus:

f_2 cycles/sec	50*	100	150	200	300	400	500	600	700	(o)
$\varphi°$	0	90	0	90	79	16	4	1	0	

*For a frequency f_2 close to f_1, but not equal to f_1, the magnetic needle performs oscillations due to the phenomenon of beats, or pulsations. However, for f_1 equal to f_2, such oscillations cease and the angle of declination phi φ above equals zero.

It is evident that the declination of the magnetic needle is due to the leakage of the constant component of the magnetic flux, arising for frequencies f_2 that are multiples of the frequency f_1 an even number of times.

We note that the phenomenon of rectification of magnetic flux was also observed at fractions of the ratios ($f_2/f_1 = p/q$) indicated above. Thus, for example, we observed angles of declination φ of the magnetic needle for frequencies f_2 equal to 20, 25, 40, 62.5, 66.6, 75 cycles/second, etc.

The phenomenon of magnetic rectification was observed for similar frequencies even after the three-legged transformer core had been replaced by two permalloy cores with the core windings connected in a somewhat different manner (the two W_1 windings on parallel, separate cores and the W_2 winding encircling both cores).

In conclusion, we note that the discussed phenomenon of magnetic rectification actually lies at the basis of the action of magnesines (V. N. Mil'shteyn, ZhTF, Vol 15, No 5-6, 248, 1945). The correct use of phenomenon of magnetic rectification will permit one to improve significantly the characteristics of magnetic amplifiers (M. A. Rozenblat, ZhTF, Vol 18, No 6, 765, 1948).

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